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Current and future conflicts between eucalypt plantations and high biodiversity areas in the Iberian Peninsula

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ABSTRACT

The Iberian Peninsula (Iberia) is a key region for preserving many endangered habitats and species. High biodiversity areas, such as Natura 2000 sites and High Nature Value farmlands, are widespread in Iberia. However, the massive, uncontrolled proliferation of exotic *Eucalyptus globulus* plantations in some regions may jeopardise conservation goals. It is thus important to assess the potential conflicts of *E. globulus* plantations with high biodiversity areas, both in current and future times. We applied *species distribution models* to project the current and future potential ranges of *E. globulus* plantations in Iberia, considering two representative concentration (of greenhouse gas) pathways (RCP): RCP2.6 and RCP8.5. Projections include a range of environmental suitability for *E. globulus* plantations. These projections were assessed in relation to the distribution of the Natura 2000 sites and High Nature Value farmlands. Conflicts were rated based on the combination between the level of suitability for plantations and the level of biodiversity importance in a grid of cells covering Iberia.

Eucalyptus globulus plantations are currently widespread inside the Natura 2000 network of the Iberian Peninsula. In a few Natura 2000 sites, *E. globulus* cover increased after their designation as a protected area. Overall, plantations expanded greatly around Natura 2000 sites. The *species distribution model* showed that the current potential range of *E. globulus* plantations extends over 18% of Iberia, mostly along the Atlantic shore, being mainly determined by the *minimum temperature of the coldest month*. The future projections show a northward contraction of the suitable range, especially under the RCP8.5 (warmer scenario). However, the suitability for *E. globulus* plantations will improve in most of the receding range, leading to an aggravation of the potential conflicts with those high biodiversity areas. This study helps identify priority areas to prevent further impacts of *E. globulus* plantations on Iberian biodiversity.

1. Introduction

Plantations of *Eucalyptus globulus* Labill. expanded vertiginously since the mid-20th century in several regions of the world (Jacobs, 1979; Potts et al., 2004), particularly in the Iberian Peninsula (Iberia), in Southwest Europe, including mainland Portugal and Spain. In Iberia, the area occupied by *E. globulus* increased about four-fold, from ca. 3,400 to 14,000 km^2, between 1970 and 2010, according to the national forest inventories. This expansion resulted mostly from a massive, uncontrolled proliferation of plantations in some regions, propelled mainly by small private landowners and pulp companies to a lesser extent, causing major landscape transformations (Calvo-Iglesias, Fra-Paleo, Crecente-Maseda, & Díaz-Varela, 2006; Ruiz & Lopez, 2010; Silva & Tomé, 2016; Teixido, Quintanilla, Carreño, & Gutiérrez, 2010). Over the last decades, *E. globulus* plantations acquired an increasing socioeconomic importance and became an important source of income for many landowners in some regions of both countries (Ruiz & Lopez, 2010; Silva & Tomé, 2016).

Iberia is a biodiversity hotspot and a key region for preserving many endangered species and habitats (Araújo, Lobo, & Moreno, 2007; Myers, Mittermeier, Mittermeier, da Fonseca, & Kent, 2000; Underwood, Viers, Klausmeyer, Cox, & Shaw, 2009). The most comprehensive effort for nature conservation in Iberia was the establishment of the Natura 2000 network of protected areas, a pan-European

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initiative promoted by the European Union aimed at protecting the most endangered terrestrial and marine species and habitats (EEA, 2017; Evans, 2012). Nearly 20% of the terrestrial Natura 2000 is located in Iberia (ca. 156,000 km^2; Portugal: 20,000 km^2; Spain; 136,000 km^2), covering 26% of the Iberia territory. The terrestrial Natura 2000 in Iberia is composed of 1505 sites (Spain: 1,409; Portugal: 96) (EEA, 2017). Iberia has also been referred to as a hotspot of High Nature Value farmlands (HNVf), corresponding to agricultural landscapes where low-intensity farming systems prevail, supporting high levels of biodiversity, including habitats and species of conservation concern (Halada, Evans, Romão, & Petersen, 2011; Paracchini et al., 2008). Despite the importance of HNVf for the conservation of the European Union natural capital, most HNVf currently occur outside protected areas, thus lacking any conservation status (EEA, 2004).

The ecological impacts of planted forests have been subject of debate. Adequate planning and management may help to conserve biodiversity (Carnus et al., 2006; Hartley, 2002), as shown in Brazil for some eucalypt plantations, through the preservation of a native understorey or native forests in their surroundings (Brockerhoff, Jactel, Parrotta, & Ferraz, 2013; Stallings, 1990). However, in some Iberian regions, a massive, uncontrolled establishment of monospecific *E. globulus* plantations may cause harmful impacts on biodiversity, by the replacement of valuable habitats (Abelho & Graça, 1996; Acácio, Dias Filipe, Catry Filipe, Rocha, & Moreira, 2016; Pozo et al., 1998) and habitat fragmentation (Fahrig, 2003; Taylor, Fahrig, Henein, & Merriam, 1993; Teixido et al., 2010). Ecological impacts of *E. globulus* plantations received much attention in recent years, particularly in Iberia (e.g. Calviño-Cancela, 2013; Castro-Díez, Fierro-Brunnenmeister, González-Muñoz, & Gallardo, 2012; Proença, Pereira, Guilherme, & Vicente, 2010; Rodríguez-Suárez, Soto, Perez, & Diaz-Fierros, 2011). Nonetheless, this is still a controversial topic as the conclusions are normally context-dependent (Poore & Fries, 1985; Richardson & Rejmánek, 2011).

Climate change is likely to have an impact in the conflicts between *E. globulus* plantations and high biodiversity areas. In fact, Iberia is expected to be one of the most responsive regions to climate change (Giorgi, 2006). As a result, tree species in Iberia will likely experience considerable range shifts (Garzón, de Dios, & Ollero, 2008), including alien tree species, which may pose new threats to biodiversity (Vicente et al., 2011). The extent of such range shifts may be determined by the magnitude of climate change (Butt, Pollock, & McAlpine, 2013; Klausmeyer & Shaw, 2009). Despite the proliferation of *E. globulus* plantations in Iberia, to date, no objective assessment has been made regarding the potential conflicts between these plantations and high biodiversity areas.

The main goal of this study was to assess the potential conflicts between *E. globulus* plantations and high biodiversity areas in Iberia, namely sites designated for conservation within the Natura 2000 network and areas identified as HNVf. Specific objectives were: a) to analyse the distribution and temporal dynamics of *E. globulus* plantations inside and around the Natura 2000 network; b) to identify the main environmental factors determining the distribution of *E. globulus* plantations; c) to use a modelling approach to project the current and future potential ranges of *E. globulus* plantations, under different climate change scenarios; d) to identify current and future potential conflicts of *E. globulus* plantations with the Natura 2000 sites and HNVf. Drawing on these results, we discuss possible future implications for biodiversity in Iberia and suggest measures to mitigate conflicts and impacts.

2. Materials and Methods

2.1. Study area

The study area includes the mainland area of Portugal and Spain (Iberia), located in the southwest of Europe, covering around 580,000 km^2. Iberia is located in the temperate zone, between ca. 36º00'N and 43º47'N. A Mediterranean climate regime predominates in Iberia, with dry and hot summers, contrasting with moist winters. Summer is hotter and dryer in the southern plateau and the Mediterranean coast, while it is cooler and wetter along the western and northern coasts due to the Atlantic influence. Overall, total annual precipitation increases from the southeast to the northwest, reaching maximum values in the northwest and north Atlantic coasts (AEMET/IM, 2011).

2.2. Study species

Eucalyptus globulus Labill. (Myrtaceae) is an evergreen tree, up to 60 m height, native to Tasmania, Bass Strait Islands and southern Victoria (Potts et al., 2004). The species is cultivated in several regions worldwide (Jacobs, 1979; Potts et al., 2004). In Iberia, it is mostly cultivated for the pulpwood and paper markets, coppiced every 10-12 years up to three rotations (Silva & Tomé, 2016). In Portugal, *E. globulus* plantations cover ca. 8,500 km^2, the equivalent to ca. 9% of the country, mostly in Central and Northwest Portugal. In Spain, plantations cover ca. 5,900 km^2, concentrated in the southwest and the northern Atlantic shores (Fig. 1). Plantations are distributed across a climatic, geological and altitudinal gradient (Catry, Moreira, Deus, Silva, & Águas, 2015; Serrada, Montero, & Reque, 2008), but greater densities of *E. globulus* plantations are found in the most productive regions (Tomé, 2000).

2.3. Assessing the dynamics of *E. globulus* in the Natura 2000

The distribution and temporal dynamics of *E. globulus* plantations inside and around the Natura 2000 network were assessed in GIS software, using vectorial maps of the Natura 2000 (EEA, 2017; Fig. 1) and vectorial land-cover maps for two time periods in each country: 1990 and 2007 for Portugal (DGT, 2007; IGP, 1990); 1996 and 2006 for Spain (MAPAMA, 2006, 1996). The 1996 land-cover map of Spain does not discriminate the eucalypt species, and should include a residual occupation of *Eucalyptus camaldulensis* Dehnh. in the southwest of Spain.

We performed three analyses. First, we assessed the current occupation of *E. globulus* in the Natura 2000 sites (Fig. 1), and verified if *E. globulus* plantations were present at the time of sites' designation. Second, we assessed the temporal dynamics of *E. globulus* plantations inside the Natura 2000 network between the time periods referred above. We restricted this analysis to the sites that were designated as protected areas before the first land-cover map for each country, i.e. we retained only the Portuguese sites designated before 1990 and the Spanish sites designated before 1996, to ensure that any expansion or reduction of *E. globulus* plantations inside the sites occurred after their designation. Additionally, among these sites, we retained only the sites that hosted *E. globulus* plantations in any of the two land-cover maps, in order to register both the expansion and the reduction of plantations in the sites along this period. Twenty-six sites fulfilled these criteria (Portugal: 12; Spain: 14), including Special Protection Areas (Birds Directive) designated since 1987 in Spain and 1988 in Portugal, that were later assimilated by the Natura 2000 designation. Third, we assessed the temporal dynamics of *E. globulus* plantations within a buffer of 1 km around the Natura 2000 sites.

2.4. Species distribution models

2.4.1. Modelling framework and assumptions

We calibrated *species distribution models* (SDM) to estimate the potential range of *E. globulus* plantations under current and future environmental conditions (IPCC, 2014) using the R package *biomod2* (Thuiller, Georges, Engler, & Breiner, 2016). As the maps of potential range include levels of environmental suitability for *E. globulus*

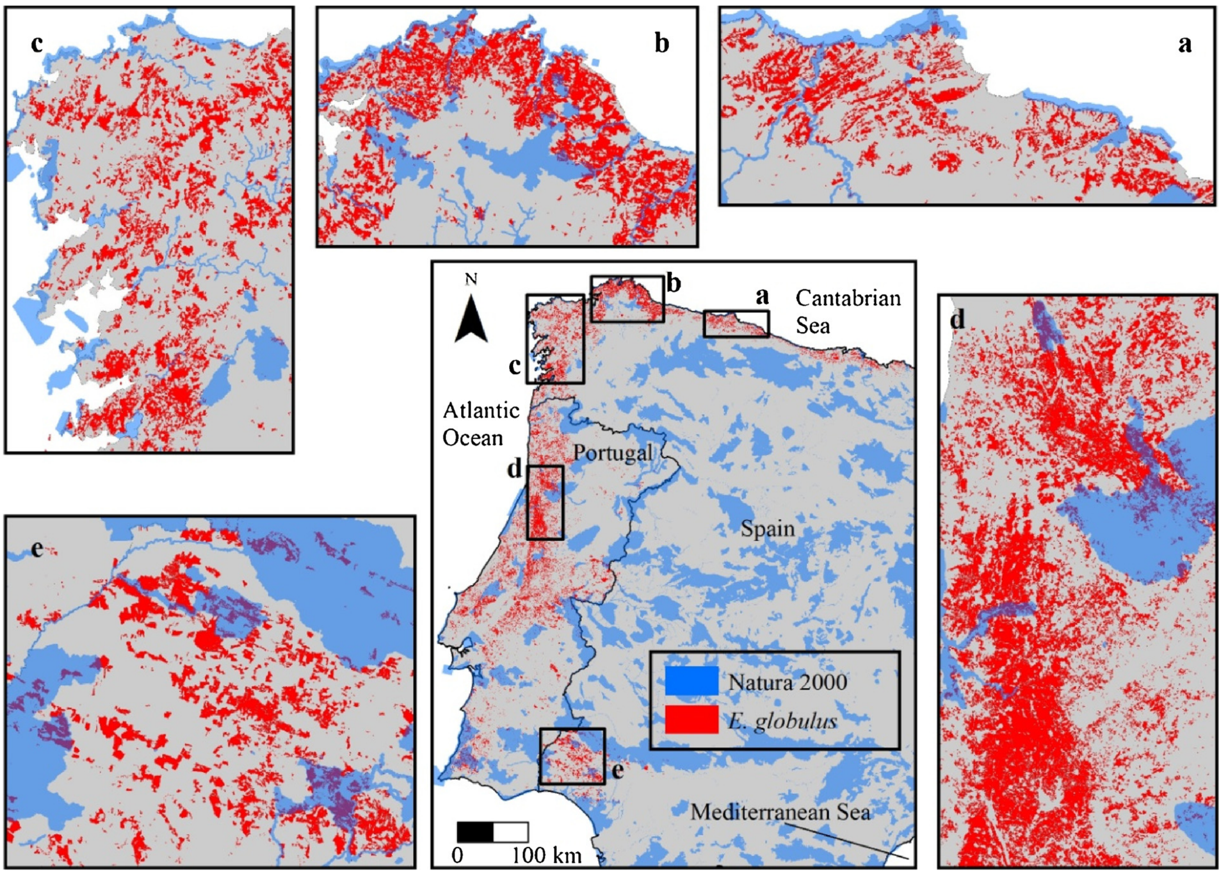

Fig. 1. Distribution of *Eucalyptus globulus* and the terrestrial Natura 2000 in Iberia. Zoom-in on representative regions featuring high density of plantations.

plantations, we assumed that locations exhibiting higher suitability have higher chances of accommodating more plantations, according to what we can actually observe in Iberia (Silva & Tomé, 2016; Tomé, 2000). This is a fair assumption considering that: most rural area in Iberia is private property (Beires, Amaral, & Ribeiro, 2013; MAGRAMA, 2012); species distribution is mostly determined by human-made decisions, because we are dealing with a cultivated species; within the suitable area for its cultivation, *E. globulus* has been the preferred forestry species by landowners. SDM are often criticized because important explanatory factors are omitted, such as biotic interactions, evolutionary changes and dispersal characteristics (Heikkinen et al., 2006; Pearson & Dawson, 2003). In this study, those limitations are minimized as: the data used to build the models were mostly from planted areas; we are dealing with a cultivated species, whose distribution is not dependent on its natural dispersal ability; the species is normally established under favourable conditions, with reduced competition with other species.

2.4.2. Presence-absence data

Data on *E. globulus* distribution was gathered from vectorial land-cover maps of Portugal (DGT, 2007) and Spain (MAPAMA, 2006). Presence of *E. globulus* was recorded at a resolution of 10×10 km, using a regular grid of cells covering Iberia, totalling 6036 cells. Presence aimed to capture the suitable areas for the species cultivation (not the species' ecological niche), since we are dealing with plantations. Therefore, *presence* was considered in any cell with a coverage $\geq 10\%$ of pure (monospecific) *E. globulus* stands, because greater coverage of plantations is normally found in the most productive areas (Silva & Tomé, 2016). The existence of pure stands should normally indicate that plantations are actively managed, thus located in productive locations, otherwise they would likely convert into mixed stands (Moreira, Vaz, Catry, & Silva, 2009). Using these criteria, presence was recorded in 334 cells. The same number of pseudo-absences ($n = 334$) was randomly selected among the *non-presence* cells. To avoid the model being skewed due to the pseudo-absence selection, the full presence set was used together with three sets of pseudo-absences randomly generated using *biomod2* function, weighting presences and pseudo-absences equally during the calculation (prevalence = 0.5; Wisz & Guisan, 2009).

2.4.3. Environmental variables as SDM predictors

A set of environmental variables was used to model the current potential range of *E. globulus* plantations in Iberia, including bioclimatic (Fick & Hijmans, 2017) and geological variables (OneGeology, 2018). Variables were chosen based on the existing knowledge about the environmental conditions determining *E. globulus* distribution (Jacobs, 1979; Kirkpatrick, 1975; Ribeiro & Tomé, 2000). Also, the selected bioclimatic variables allowed forecasting future climate data (see Section 2.4.5). Only variables presenting pairwise *Spearman* correlations < 0.7 were retained. When variables were correlated, we chose the one with the most direct ecological impact (based on expert knowledge) on plant species distribution (Guisan & Thuiller, 2005). This analysis yielded a final set of 14 variables: seven bioclimatic and seven geological variables (Table 1). The importance of each environmental variable was estimated for the ensemble model prediction (Thuiller et al., 2016).

2.4.4. Model calibration and evaluation

Mopdel calibration and evaluation were performed using the ten available modelling algorithms of the *biomod2* package (for more details see *biomod2* help files and vignettes) and the selected set of 14 environmental variables. Each individual model was calibrated using 80% of available data. The area under the curve (AUC) was then calculated on the 20% of remaining data. The final ensemble model was

Table 1
Original sets of bioclimatic and geological variables considered to model the potential range of *Eucalyptus globulus* plantations. Asterisks indicate uncorrelated variables selected for modelling calibration. Sources: bioclimatic variables (Fick & Hijmans, 2017); geological variables (OneGeology, 2018)

Type of variables	Variables
Bioclimatic	Annual Mean Temperature
	Mean Diurnal Range
	Isothermality*
	Temperature Seasonality*
	Maximum temperature of the warmest month
	Minimum temperature of the coldest month*
	Temperature annual range
	Mean temperature of the wettest quarter*
	Mean temperature of the driest quarter
	Mean temperature of the warmest quarter
	Mean temperature of the coldest quarter
	Annual Precipitation*
	Precipitation of the wettest month
	Precipitation of the driest month
	Precipitation seasonality*
	Precipitation of the wettest quarter
	Precipitation of the driest quarter
	Precipitation of the warmest quarter*
	Precipitation of the coldest quarter
Geological	Felsic and intermediate igneous rocks*
	Mafic igneous rocks*
	Non foliated metamorphic rocks*
	Foliated metamorphic rocks*
	Carbonate sedimentary rocks*
	Water*

obtained by the predictions of all models with AUC above 0.7, using the Mean (all) consensus method (see Marmion, Parviainen, Luoto, Heikkinen, & Thuiller, 2009).

Model projection was reclassified into a probability ramp using a threshold maximizing the percentage of presences and absences correctly predicted (i.e. the probability where sensitivity = specificity; Liu, Berry, Dawson, & Pearson, 2005) to classify absences, and then a probabilistic ramp from the threshold to the maximum predicted value using the "filtROC" function available in *biomod2* (for more details see *biomod2* help files and vignettes). The probability ramp can be assumed as a degree of environmental suitability for the establishment of *E. globulus* plantations.

2.4.5. Projecting current and future ranges of E. globulus plantations

After calibration, we projected the current and future potential ranges of *E. globulus* plantations in Iberia. The potential range was classified according to five levels of environmental suitability for *E. globulus* plantations: 1: not suitable (< 1%); 2: very low suitability (1-25%); 3: low suitability (26-50%); 4: high suitability (51-75%); 5: very high suitability (76-100%). To project the models of *E. globulus* plantations range under future climatic conditions, we chose two plausible and accessible socio-economic scenarios from the Intergovernmental Panel on Climate Change (IPCC, 2014) for the years 2050 and 2070, corresponding to two contrasting representative concentration (of greenhouse gas) pathways (RCP): RCP2.6 and RCP8.5. The RCP2.6 assumes a global development following sustainable locally oriented pathways, with lower rates of global population growth and yielding moderate increases in temperature, between 0.3 °C and 1.7 °C in the late-21th century. The RCP8.5 assumes a very rapid economic growth with increasing globalisation, a balanced requirement of different fossil and non-fossil energy sources, leading to a great increase in temperature, ranging between 2.6 °C and 4.8 °C in the late-21th century (IPCC, 2014; Moss et al., 2010). The intermediate year of 2050 was included because the RCP2.6 considers an inversion on greenhouse gas concentration around this period. Only bioclimatic variables were used in the models. For each bioclimatic variable, under each RCP/year, a consensus map (average values) was produced using all available general circulation models (14 in common for both RCPs; Fick & Hijmans, 2017). As a result, this study presents five projections: 1) current potential range; future potential ranges under the RCP2.6 for the years 2) 2050 and 3) 2070; future potential ranges under the RCP8.5 for the years 4) 2050 and 5) 2070.

2.5. Rating conflicts with biodiversity areas

The distribution of HNVf was produced by upscaling the map from Paracchini et al. (2008) to a 10 × 10 km grid of cells. A "conflict" was defined as the co-existence, in the same 10 × 10 km cell, of *E. globulus* plantations and biodiversity areas, namely Natura 2000 and HNVf sites. Conflicts were rated based on the different combinations between the level of environmental suitability for *E. globulus* plantations and the level of importance of biodiversity areas in each cell, namely the number of Natura 2000 sites in each cell (no sites: less important biodiversity; 1-2 sites: important biodiversity; ≥3 sites: very important biodiversity) and, for HNVf, in conformity with the criteria from Paracchini et al. (2008), the likelihood of each grid cell to exhibit high nature value (0%: less important biodiversity; 1-50%: important biodiversity; > 50%: very important biodiversity) (Table 2).

3. Results

3.1. Is E. globulus expanding inside and around the Natura 2000 network?

In 2006/7 (Spain/Portugal), nearly 10% (1,463 km^2) of the area of *E. globulus* plantations in Iberia was distributed across 235 areas currently designated as Natura 2000 (Portugal: 1,026 km^2; Spain: 437 km^2). On average, *E. globulus* plantations covered 5.8% of these areas (n = 235), reaching more than 20% cover in 21 areas, and more than 50% in four areas. There were at least 150 Natura 2000 sites which hosted *E. globulus* plantations at the time of designation, 16 of which exhibited a cover higher than 20%.

The dynamics of *E. globulus* plantations inside Natura 2000 after site's designation was assessed on 26 sites (see also Section 2.3). Overall, between 1990/96 (Portugal/Spain) and 2006/7, *E. globulus* cover decreased ca. 37% (from 343 to 215 km^2), even though it increased in 19 out of the 26 sites (73%). A thorough analysis of this result revealed that the overall reduction was mainly influenced by three sites in southwest Spain (Andalusia). In fact, without these three

Table 2
Rating of the conflicts between *Eucalyptus globulus* plantations and biodiversity areas

Levels of suitability for *E. globulus* plantations	Levels of biodiversity importance: Very important biodiversity	Important biodiversity	Less important biodiversity
Very high (> 75%)	Highest concern [7]	Probable conflict with high concern [6]	No conflict but suitable conditions for plantations [2]
High (51–75%)	Conflict possible with very high concern [5]	Conflict possible with high concern [4]	
Low (26–50%)			
Very low (1–25%)	Lowest concern [3]		
Unsuitable (< 1%)	No conflict [1]		

The rating of conflicts for the Natura 2000 and HNVf was merged in a single table for convenience, since the analyses were conducted separately. Numbers between square brackets (from 1 to 7) find correspondence with the levels of conflict in Figs. 4 and 5.

sites, *E. globulus* cover would have increased 34% (from 105 to 141 km^2). At a country-level, in Portugal (n = 12), the area occupied by *E. globulus* increased 48% (from 29 km^2 to 43 km^2; +0.8 km^2 $year^{-1}$), while in Spain (n = 14) it decreased 45% (314 km^2 to 172 km^2; -14 km^2 $year^{-1}$). Again, without the three sites in southwest Spain, the area occupied by *E. globulus* in the Spanish sites would have increased 32% (from 75 to 99 km^2; +2.4 km^2 $year^{-1}$). Note that the reduction of *E. globulus* plantations in southwest Spain can also be partly explained by the fact that, in the first land-cover map (MAPAMA, 1996), an undefined amount of *E. camaldulensis* plantations was accounted as *E. globulus* plantations (see Section 2.3).

Around the a

reas currently designated as Natura 2000 (1 km buffer), the *E. globulus* cover increased 71% between 1990/6 and 2006/7 (from 853 to 1,457 km^2). Around the Portuguese sites, the *E. globulus* cover increased 46% (from 388 to 567 km^2), while around the Spanish sites it increased 69% (from 589 to 995 km^2).

3.2. What is the current potential range of E. globulus plantations?

Overall, the goodness of the ensemble model denoted an excellent accuracy, with an AUC of 0.964. The current potential range of *E. globulus* plantations was found to be mainly determined by two bioclimatic variables: the *minimum temperature of the coldest month* (44.8% importance; positive effect); and, the *temperature seasonality* (10.5% importance; negative effect). The remaining variables had an importance below 10% (see the importance of all variables in Appendix A, Table A1; see model plots in Appendix B, Fig. B1 and B2).

The current potential range of *E. globulus* plantations extends over 106,800 km^2 along most of the Atlantic shore, corresponding to ca. 18% of Iberia. The species' range is wider in southwest Iberia, reaching ca. 200 km from the coastline, and progressively narrows towards the north, ending in a thin coastal strip along the northern shores (Fig. 2). Most (72%) of the "suitable range" exhibits *high* (28%) or *very high* (44%) suitability. The lowest suitability for *E. globulus* plantations is observed in southwest Iberia and along the inner boundaries of the suitable range. In 2006/7, *E. globulus* plantations occupied 13.4% of the current potential range, according to the following distribution: 63% in *very high suitability* areas; 22% in *high suitability* areas; 8% in *low suitability* areas; 3% in *very low suitability* areas; 4% in *unsuitable* areas (Fig. 2). Similar patterns of distribution were found in the two Iberian countries.

3.3. How will E. globulus plantations be distributed in the future?

In 2070, the suitable range of *E. globulus* plantations is expected to decrease to 92% and 55% of the current extent under the RCP2.6 and the RCP8.5, respectively. The loss of suitable range is expected to occur mostly in southwest Iberia. This loss is much more expressive under the RCP8.5, where large contiguous clumps of suitable range are lost in each time frame (Fig. 3).

Both RCP scenarios show a gain of suitable range in the northern inner boundaries, which is greater under the RCP8.5 (see Appendix B: Fig. B3). In the year 2070, under the RCP8.5, the suitable range begins to disappear along the shore of the Cantabrian Sea. Within the suitable range, the proportion of *very high* suitability areas increases from 44% (47,200 km^2) on the current potential range, to 69% (67,900 km^2) and 62% (37,000 km^2) in 2070 under the RCP2.6 and the RCP8.5, respectively (see Appendix A: Table A2).

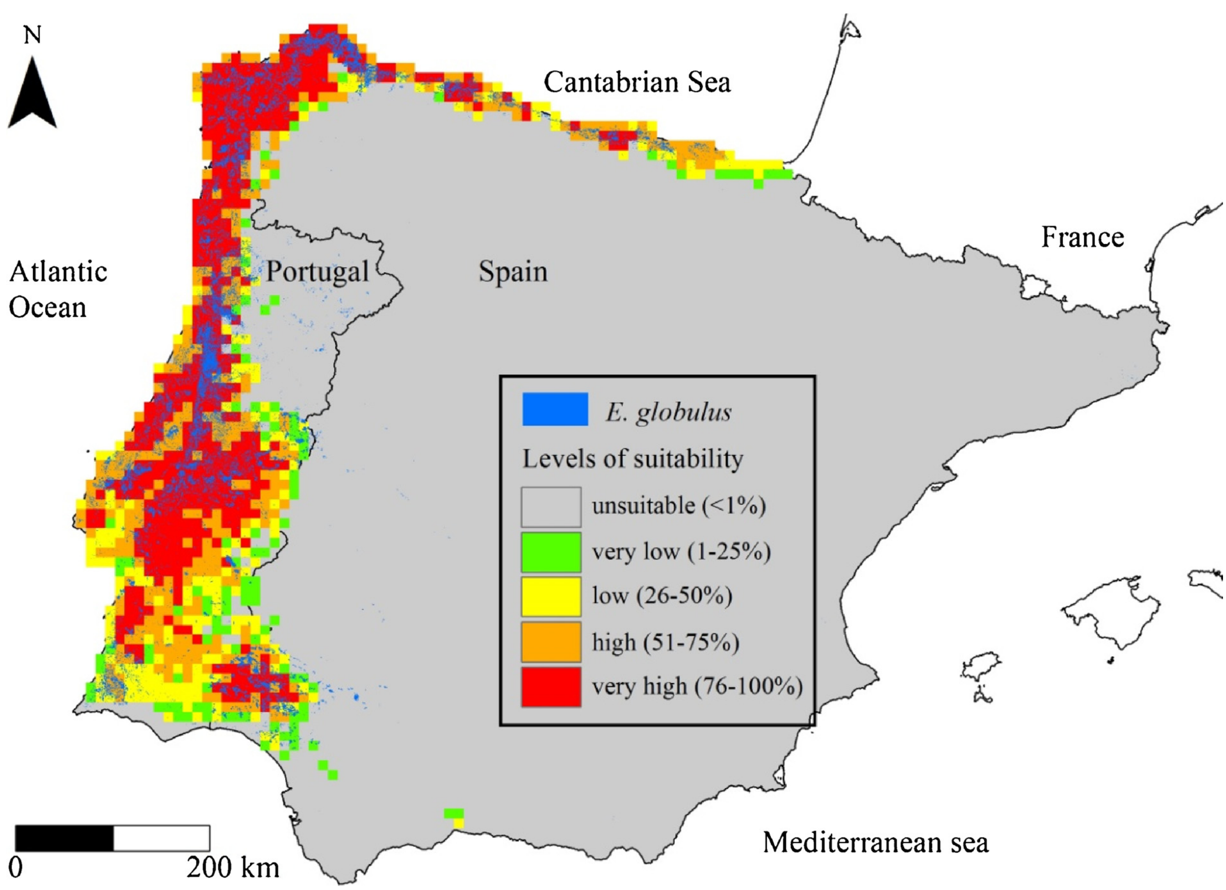

Fig. 2. Distribution of *Eucalyptus globulus* plantations (blue) over the current potential range. The potential range includes levels of environmental suitability for plantations.

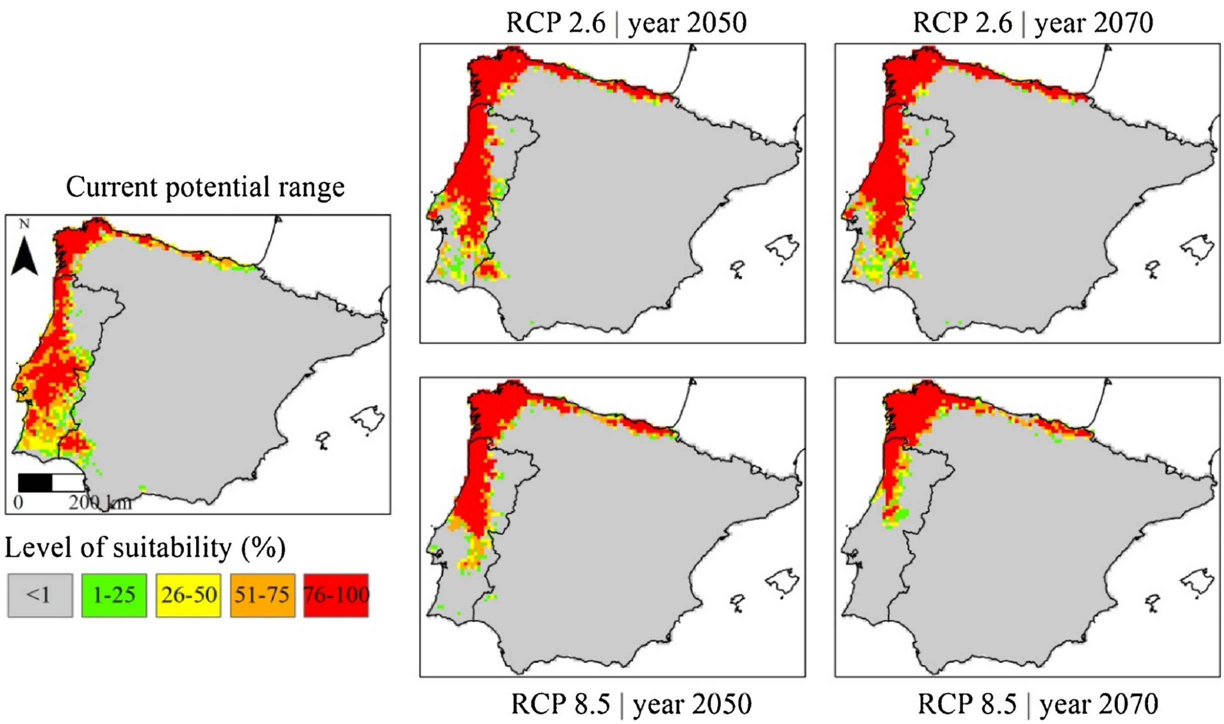

Fig. 3. Current potential range of *Eucalyptus globulus* plantations and future potential ranges for the years 2050 and 2070 under the RCP2.6 and the RCP8.5 scenarios. The potential range is classified according to levels of environmental suitability for plantations.

3.4. Where are conflicts with Natura 2000 expected to occur?

According to our projections, in 2070, the extent of *conflict* between *E. globulus* plantations and Natura 2000 areas, i.e. the number of cells combining the existence of Natura 2000 sites and suitable conditions for plantations, is expected to decrease 13.7% under the RCP2.6 and 41.7% under the RCP8.5 compared to the current potential range. Likewise, the number of Natura 2000 sites located within the suitable range of *E. globulus* plantations will decrease from 254 to 244 sites under the RCP2.6, and to 196 sites under the RCP8.5. These results depict the balance between the number of Natura 2000 sites maintained, lost and added by a shifting range until the year 2070, totalling, respectively, 215, 39 and 29 sites under the RCP2.6, and 142, 112 and 54 sites under the RCP8.5.

In the current potential range, the most concerning *conflict areas*, classified as *highest concern* (level 7; see Table 2) and *probable conflict with high concern* (level 6), cover 2,590 km^2 (25% of the range). Under the RCP2.6, the extent of level 6-7 conflict areas increases to 4,010 km^2 in 2070 (41%), while under the RCP8.5 it increases to 3,180 km^2 in 2050 (43%), followed by a decrease to 2,470 km^2 in 2070 (42%; see also Appendix A: Table A3). Under both RCPs, level 6-7 conflict areas concentrate along the northern shore and northwest Iberia. There is also an expansion of level 6-7 conflict areas in the northern half of Portugal, which seems to cease before 2070 under the RCP8.5 (Fig. 4).

3.5. Where are conflicts with High Nature Value farmlands expected to occur?

Between the current and the 2070 projection, the extent of the *conflict area* with HNVf, i.e. the number of cells featuring HNVf and suitable conditions for *E. globulus* plantations, is expected to decrease 8.2% under the RCP2.6 and 54% under the RCP8.5. In the current potential range, the areas exhibiting the higher levels of conflict, *highest concern* (level 7; see Table 2) and *probable conflict with high concern* (level 6), cover 1,710 km^2 (16% of the suitable range). Under the RCP2.6, the extent of level 6-7 conflict areas increases to 2,660 km^2 in 2070 (28%), while under the RCP8.5 it decreases to 1,330 km^2 in 2070, even though their representativeness increases to 22% of the suitable range (see also Appendix A: Table A4). Under both RCPs, there is an expansion of level 6-7 conflict areas along the northern Spanish shore, in the northwest of Spain and, particularly under the RCP2.6, in Central Portugal and the northern half of Portugal (Fig. 5).

4. Discussion

4.1. Dynamics of E. globulus plantations in the Natura 2000

Eucalyptus globulus plantations are currently spread across 235 Natura 2000 sites, occupying a considerable area in some sites. Nearly 70% of the *E. globulus* cover inside the Natura 2000 network was found inside Portuguese sites, even though the extent of the terrestrial Natura 2000 is ca. seven times greater in Spain. This disparity between countries may be partly explained by the fact that: Portugal is more than five times smaller than Spain; the total area of *E. globulus* plantations is nearly 1.4 larger in Portugal; the current potential range of *E. globulus* plantations covers most of Portugal, as well as most of the Portuguese Natura 2000 sites, in contrast to a small fraction of Spain. Both countries have restrictive regulations on protected areas. Therefore, it is likely that *E. globulus* plantations preceded these protected areas. In fact, we found that *E. globulus* plantations were already present in most of the Natura 2000 sites at the time of designation as a protected area, which is symptomatic of the ubiquity of these plantations. On the other hand, it may suggest that *E. globulus* plantations can co-exist with areas of high biodiversity value, even though there are reports of negative impacts associated with *E. globulus* plantations inside protected areas (e.g. Teixido et al., 2010).

In a small sample of Natura 2000 sites, we found an overall reduction of the coverage of *E. globulus* plantations after their designation as protected areas. This reduction was most expressive in southwest Spain, likely as a result of an inversion of regional forestry policies that led to the removal of eucalypt plantations (Álvarez, 2011; Ovando, Campos, Montero, & Ruiz-Peinado, 2009). However, *E. globulus*

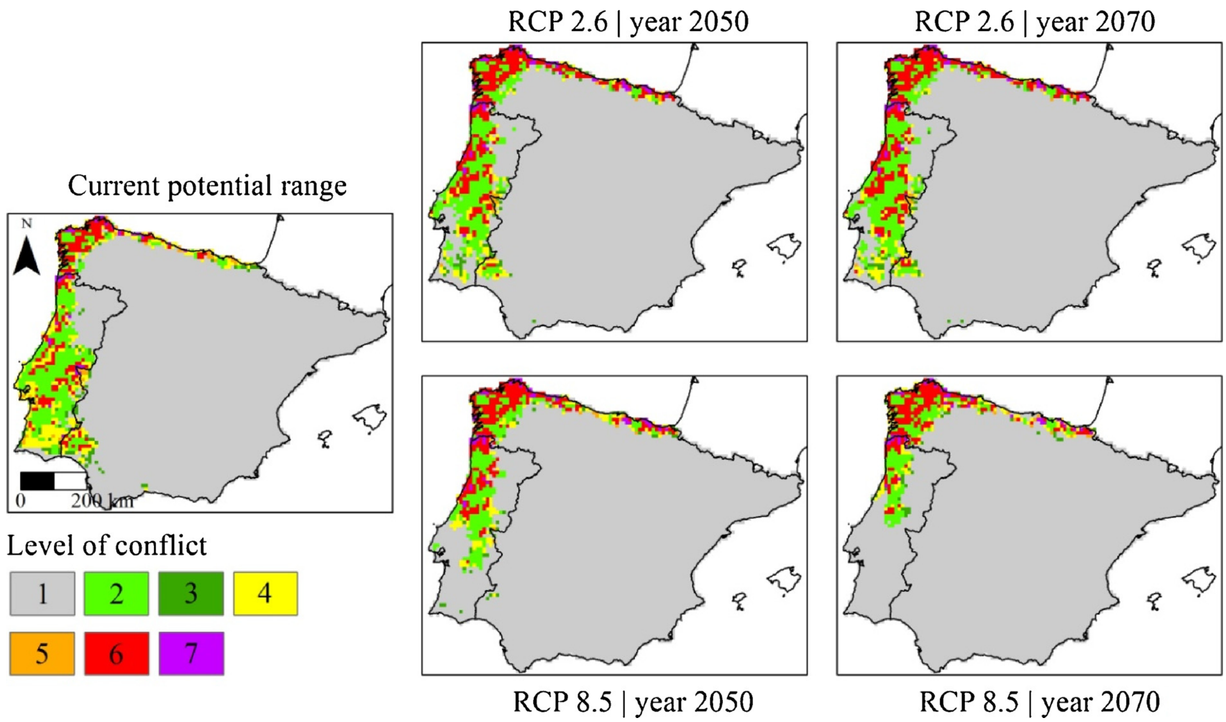

Fig. 4. Levels of conflict between *Eucalyptus globulus* plantations and Natura 2000 sites for current times and for the years 2050 and 2070 under the RCP2.6 and the RCP8.5 scenarios. The levels of conflict correspond to: 1: no conflict; 2: no conflict but suitable conditions for plantations; 3: lowest concern; 4: conflict possible with high concern; 5: conflict possible with very high concern; 6: probable conflict with high concern; 7: highest concern (see Table 2).

plantations expanded in a small number of sites, both in Portugal and Spain. In Portugal, a governmental report acknowledged that *E. globulus* plantations replaced important habitats, being one of the threats to some habitats and species (ICNB, 2008). Such land-cover changes inside the Natura 2000 network most probably eluded the prevailing regulations or the site's management plan when existent, suggesting a lack of supervision and law enforcement. Around the Natura 2000 sites, there was a substantial expansion of *E. globulus* plantations. On one hand, it suggests that the conservation status of the Natura 2000 sites has prevented a higher expansion of plantations. On the other hand,

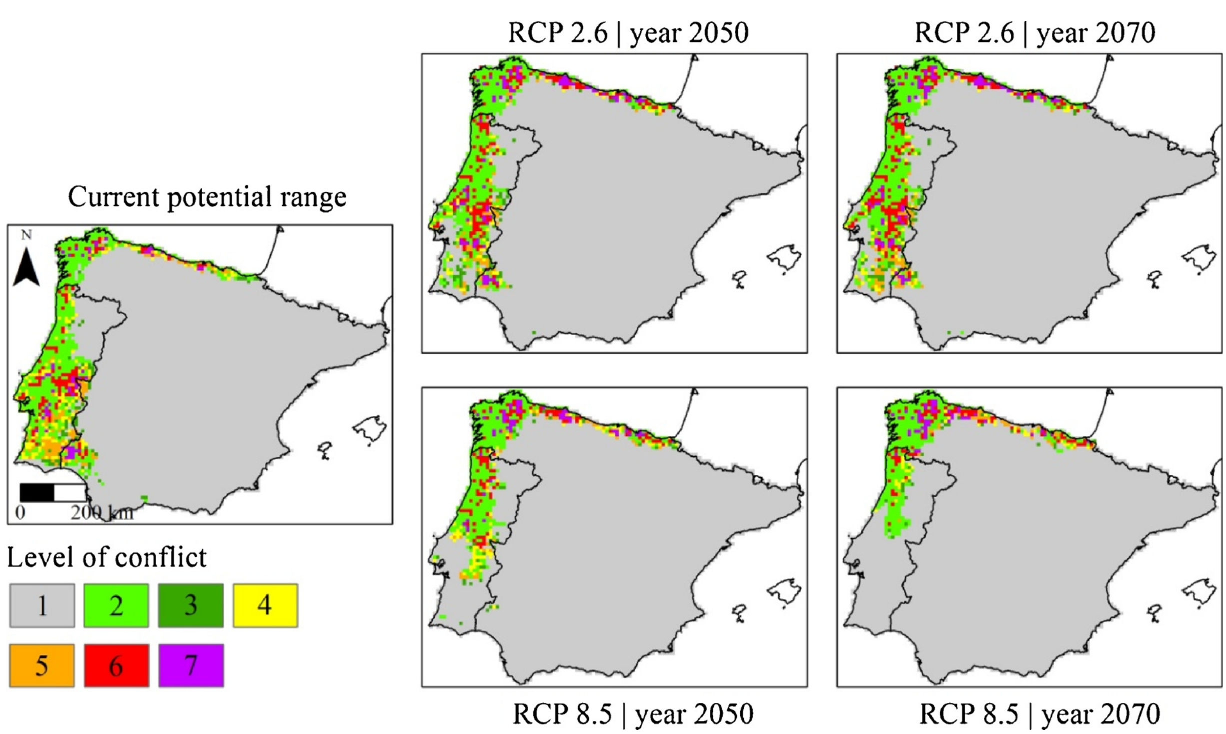

Fig. 5. Levels of conflict between *Eucalyptus globulus* plantations and High Nature Value farmlands for current times and for the years 2050 and 2070 under the RCP2.6 and the RCP8.5 scenarios. The levels of conflict correspond to: 1: no conflict; 2: no conflict but suitable conditions for plantations; 3: lowest concern; 4: conflict possible with high concern; 5: conflict possible with very high concern; 6: probable conflict with high concern; 7: highest concern (see Table 2).

such an expansion suggests that the surroundings of the Natura 2000 sites have been neglected.

4.2. The current potential range of E. globulus plantations

Temperature-related variables were determined to explain the current potential range of *E. globulus* plantations, especially the *minimum temperature of the coldest month*, reflecting the sensitivity of small *E. globulus* seedlings to frost (Jacobs, 1979; Kirkpatrick, 1975). The low tolerance of *E. globulus* to wide variations in temperature should explain the proliferation of plantations along the Atlantic shore, where temperature extremes are attenuated (AEMET/IM, 2011). Areas of *high* and *very high suitability* for *E. globulus* plantations predominate in most of the current potential range. However, there are likely some artifices, particularly in the *very high suitability* of some regions in the southern half of Portugal and in the southwest of Spain. This artifice is caused by the abundance of *E. globulus* plantations in these regions characterized by a lower productivity (Álvarez, 2011; Ribeiro & Tomé, 2000), suggesting that *E. globulus* plantations may also expand in disadvantaged areas. There are also a few scattered plantations outside the potential range, probably occupying the limits of the species' tolerance in terms of rainfall shortage and temperature seasonality. In fact, in the southwest of Spain, *E. globulus* plantations overlap the range of *Eucalyptus camaldulensis* Dehnh. (MAPAMA, 2006), a species with greater tolerance to drought and extreme temperatures (Jacobs, 1979).

4.3. Future potential ranges of E. globulus plantations

Eucalyptus globulus plantations are expected to experience considerable range shifts due to climate change, like many native tree species (Garzón et al., 2008). The range shift will be determined by the magnitude of climate change, as observed in other studies (Butt et al., 2013; Klausmeyer & Shaw, 2009). Under the RCP2.6, the loss of suitable range is practically negligible, and even tends to recover following the mid-century inversion on greenhouse gas concentration. In contrast, under the RCP8.5, the suitable range will be confined to nearly half of the original extent in 2070, with the loss of suitable range progressing northwards along this period. Both scenarios suggest, with different magnitudes, a poleward shifting of *E. globulus* plantations, as predicted for many other plants and animals (Harrison, Berry, Butt, & New, 2006; Hickling, Roy, Hill, Fox, & Thomas, 2006). In Iberia, this *migration* is inevitably blocked by the Cantabrian Sea, resulting in a range contraction.

The contraction of the suitable range of *E. globulus* plantations does not necessarily imply a reduction of the area occupied by *E. globulus*. In fact, in both climate change scenarios, the range contraction may be counterbalanced for at least four reasons. First, new suitable areas for *E. globulus* plantations will likely emerge in the northern inner borders of the range, where there may be greater potential in terms of space for accommodating new plantations. Second, the loss of suitable range does not necessarily mean that *E. globulus* plantations will be removed from the areas that became unsuitable for cultivation. Older plantations in these areas will probably become abandoned (as currently happens), with no productive or conservation utility. Third, market demands, following the decrease of productive plantations due to the shrinking range, may encourage the establishment of new plantations, including in areas of lower productivity, as we see today in Iberia. Finally, many areas currently exhibiting lower suitability for *E. globulus* plantations will become of *very high suitability*, meaning that the cultivation of *E. globulus* plantations will become much more appealing in these areas, encouraging the establishment of new plantations.

Nevertheless, the future projections omit several factors, particularly anthropic drivers, which may help to shape the future distribution of *E. globulus* plantations. Governments in both countries have been developing legislation to control and regulate the establishment of *E. globulus* plantations. We cannot forecast future policies (and their efficiency), socioeconomic changes or market demands, which may severely limit, revert or perhaps even encourage the expansion of *E. globulus* plantations, resulting in more or less distinct scenarios than the ones we present.

4.4. Conflicts with high biodiversity areas

The reduction of the extent of conflict areas with both Natura 2000 and HNVf is a direct result of the contraction of the suitable range of *E. globulus* plantations. Despite range contraction, the suitability for plantations is expected to improve (to *very high suitability*) on a larger portion of the suitable range, leading to an aggravation of conflicts. These trends are shared by the two types of biodiversity areas because both are fairly distributed across the potential range of *E. globulus* plantations, and because they partly overlap, since some HNVf integrate with Natura 2000 (Halada et al., 2011; Paracchini et al., 2008). In the case of Natura 2000, under both climate change scenarios, northwest Iberia (including the northwest of Spain and the northwest of Portugal) is the region where the most serious conflicts are expected. However, under the RCP2.6, other regions were found to be particularly concerning, namely the northern Spanish coast and Central Portugal. Areas of conflict between *E. globulus* plantations and HNVf are more scattered but, under both RCPs, relatively large extensions of these areas are expected to be found in northwest Iberia and the northern Spanish coast. Under the RCP2.6, in particular, the highest number of conflicts with HNVf is also expected to occur in Central Portugal.

There is a trade-off between conflict extent and conflict level on the two climate change scenarios. On one hand, under the RCP2.6, there are more high biodiversity areas under potential conflict, because the suitable range of *E. globulus* plantations is wider. On the other hand, the materialization of conflicts, and their exacerbation, is more likely under the RCP8.5, because *E. globulus* plantations will be confined to a smaller area, causing a greater concentration of plantations. Therefore, both scenarios of climate change are potentially harmful for both types of biodiversity areas following the possible range dynamics of *E. globulus* plantations. Apart from these considerations, it should be consensual that the RCP8.5 is the worst of these scenarios, because climate change itself is a major threat to biodiversity (Pacifici et al., 2017; Thomas et al., 2004). It is also worth mentioning that, without additional efforts to constrain greenhouse gas emissions, the RCP8.5 is considered to be a more likely scenario (IPCC, 2014).

4.5. Mitigating the conflicts and impacts

The socioeconomic importance of *E. globulus* in both Iberian countries requires efforts in reconciling *E. globulus* plantations with nature conservation goals. It is known that adequate planning and management can alleviate the potential negative impacts of planted forests (Brockerhoff, Jactel, Parrotta, Quine, & Sayer, 2008; Fischer, Lindenmayer, & Manning, 2006; Hartley, 2002), as shown in some Brazilian eucalypt plantations, by maintaining a native understorey or preserving native forests in the surrounding landscape (Brockerhoff et al., 2013; Stallings, 1990). However, ecological benefits will hardly be achieved with the uncontrolled, massive expansion of mono-specific *E. globulus* plantations in some Iberian regions. Governments in both Iberian countries have been implementing legislation to control and regulate the expansion of *E. globulus* plantations, but it has proven to be flawed and inadequate to address local realities. This study shows that particular attention should be devoted to the potential impacts on high biodiversity areas, and helps identify the areas of greatest concern in current and future times.

The proliferation of *E. globulus* plantations around Natura 2000 sites is of major concern due to the potential of hindering connectivity between sites. Management of *E. globulus* plantations towards the preservation of a native understorey would likely enhance landscape connectivity (Calviño-Cancela, Rubido-Bará, & van Etten, 2012). HNVf

can play a key role connecting protected areas. HNVf require particular attention because, apart from other threats such as wildfires, socio-economic changes (e.g. rural exodus, agriculture intensification) are leading to their decline and most of them lack conservation status (Jongman, 2002; Plieninger, Höchtl, & Spek, 2006; Stoate et al., 2009). Besides, their mapping, the records of their biodiversity and their monitoring are still deficient (EEA, 2004; Lomba et al., 2014). The efforts to preserve these agricultural systems should prioritize the ones which may enhance the connectivity between protected areas and promote landscape heterogeneity. In this regard, protected areas like the Natura 2000 sites should feature a surrounding safety zone with specific planning and regulation, particularly in relation to landscape planning, land-use and forest management to promote species movement and gene flow, and prevent harmful impacts on vulnerable habitats and species, including wildfires and alien plant invasions.

Several authors denounced the fragilities of the Natura 2000 network, such as the deficient planning, management and monitoring, insufficient funding, ineffective law enforcement, disaffection of landowners and conflict of interests with landowners (Apostolopoulou & Pantis, 2009; Fuentes, Otón, Quintá, & Arce, 2011; Geitzenauer, Hogl, & Weiss, 2016; Wätzold et al., 2010). In Iberia, the overwhelming predominance of a highly fragmented private property, particularly in the regions where *E. globulus* plantations find the best conditions for cultivation, is an overarching constraint to overcome these deficiencies. Therefore, landowners are key stakeholders for conservation efforts (Carvalho-Ribeiro, Lovett, & O'Riordan, 2010; Fuentes et al., 2011).

In this study we considered high biodiversity areas to be static. However, like *E. globulus* plantations, many endangered species in the Natura 2000 may lose suitable climate in current locations (Araújo, Alagador, Cabeza, Nogués-Bravo, & Thuiller, 2011), and will be forced to migrate, on their own or by human assistance, also towards the north and higher altitudes (Hickling et al., 2006; Lenoir, Gégout, Marquet, de Ruffray, & Brisse, 2008; Pereira et al., 2010). It is thus fair and wise to foresee the need to create new protected areas or expand the existing ones, particularly in the northern regions of Iberia. However, future conservation efforts may become jeopardised by the current occupation of *E. globulus* plantations, but also by the possible expansion of plantations in the absence of effective law enforcement (Santos et al., 2016). It is thus urgent to prevent and, preferably to revert, the expansion of *E. globulus* in the regions that may form future refuges for the Iberian biodiversity.

5. Conclusions

The current potential range of *E. globulus* plantations extends over 18% of Iberia, mostly along the Atlantic shore, being strongly influenced by the *minimum temperature of the coldest month*. *Eucalyptus globulus* plantations are currently widespread within the Natura 2000. Many Natura 2000 sites already hosted *E. globulus* plantations at the time of designation. However, we found that *E. globulus* plantations have expanded inside some Natura 2000 sites. Moreover, *E. globulus* plantations have been proliferating around Natura 2000 sites. We expect a northward contraction of the suitable range of *E. globulus* plantations, much more expressively under the worst climatic scenario (RCP8.5), as a result of the loss of suitable range in the southwest. Despite the contraction of the suitable range, conflicts with both Natura 2000 and HNVf are expected to worsen under both climate change scenarios. In fact, for each climate change scenario, in each year (2050 and 2070), the extent of the areas exhibiting the most concerning conflicts will increase either in absolute terms (total surface), relative terms (fraction of the total suitable range) or in both. The potential expansion of *E. globulus* plantations in the absence of effective law enforcement may seriously jeopardise future conservation efforts. This study identifies the areas of highest concern, where corrective and preventive measures are more critical.

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